Principles of Reactor Safety Notes

This presentation addresses the focus of nuclear reactor safety provided by a 3-level defense-in-depth protocol

Slide 2 – key to proper operation of nuclear power plant is that heat removal rate from reactor core must match heat generation rate

- if heat generation rate exceeds heat removal rate potentially damaging plant condition could be created, depending on magnitude of excursion and duration, where fuel integrity compromised
- while shutting down fossil-fueled power plant terminates heat generation, nuclear power plant continues to generate heat following shutdown from radioactive decay of fission products in nuclear fuel
- decay heat must be removed for weeks following reactor shutdown to keep fuel from overheating and ultimately melting
- uranium oxide fuel pellets and fuel rods containing pellets are first and second engineered barriers to prevent radioactive material release – integrity must be preserved by continuing to remove radioactive decay heat

Slide 7 – reactor neutron population

- neutron population control absolutely essential to controlling reactor power
- at steady-state power neutron multiplication factor is one; that is, neutron production from fission equals neutron losses by capture (fission and absorption) and system losses
- neutron population can’t be measured directly; some other related and measurable parameter necessary to adequately control reactor neutron population

Slide 8 – reactor reactivity defined

- more will be said about system reactivity in How a Nuclear Reactor Works presentation; for now, just note that
  - at steady-state power system reactivity is zero (i.e., $k-1 = 0$)
  - system reactivity change greater than zero causes neutron population to increase ($k-1 > 0$), which increases reactor power
  - system reactivity change less than zero causes neutron population to decrease ($k-1 < 0$), which decreases reactor power

Slide 11 – PWR reactor vessel graphic

- graphic shows control rod configuration for PWR

- control rods enter reactor core from above and control rod drives located at top of reactor vessel
- rapid insertion of control rods for reactor shutdown accomplished by removing electrical power to control rod drive mechanisms, which disconnects control rods from drive mechanisms; control rods driven into reactor core by gravity

Slide 12 – BWR reactivity control systems

- preferred method for controlling core reactivity in BWR is by controlling amount of boiling that occurs in reactor core
  - reducing coolant flow through reactor core results in more coolant voids (from more boiling), reducing neutron moderation and fuel fission rate (power)
  - increasing coolant flow through reactor core results in fewer coolant voids, increasing neutron moderation and fuel fission rate

Slide 13 – BWR reactor vessel graphic

- graphic shows the control rod configuration for BWR
- because of moisture separators and steam dryers located in top of reactor vessel, control rods (blades) enter reactor core from below and control rod drives located at bottom of reactor vessel
- during reactor operation, safety control rods withdrawn below core
- rapid insertion of control rods for reactor shutdown accomplished using high pressure nitrogen to drive control rods into reactor core

Slide 14 – reactivity feedback mechanisms

- fuel temperature, moderator temperature, and moderator void reactivity coefficients oppose initiating reactivity change in reactor core, restoring core reactivity to zero, but at different power level
  - increase in fuel temperature caused by increased fission rate (heat generation rate) results in enough expansion of fuel assembly dimensions to reduce number of fission events, thereby limiting fission rate increase
  - increase in moderator temperature or moderator voids caused by increased fission rate results in decrease in neutron moderation that reduces number of fission events, thereby limiting fission rate increase

Slide 15 – automatic reactivity control graphic

- graphic illustrates how feedback from fuel temperature, moderator temperature, and moderator void reactivity coefficients automatically controls changes in system reactivity

- fuel temperature, moderator temperature, and moderator void coefficients are negative in LWRs
- negative reactivity feedback quickly opposes planned or inadvertent positive changes in core reactivity
- negative reactivity coefficients provide assurance of controllable rate of change for reactor power level increases

Slide 17 – BWR operational heat removal

- heat removal during normal BWR operation by means of conventional steam cycle power plant
- steam from reactor operates steam turbine-generator
- low pressure, low temperature steam from turbine exhaust condensed back to water and pumped back to reactor
- BWR plants generally have two recirculating coolant loops to remove heat from reactor core

Slide 18 – PWR operational heat removal

- PWR heat removal similar to BWR except that steam generated in steam generator located inside reactor containment building
- because reactor coolant system operated at very high pressure, water doesn't boil
- heat from high-pressure primary coolant water transferred to low pressure secondary coolant water to create steam in steam generator
- cooler primary coolant water exiting steam generator pumped back to reactor core
- water from steam cycle power plant condenser pumped back to steam generator
- PWR plants have two, three, or four recirculating reactor coolant loops, depending on plant design, to remove heat from reactor core

Slide 21 – decay heat graphic

- decay heat graphic from Fukushima Daiichi Units 1, 2, and 3 illustrates typical decay heat power (in megawatts) that continues to be generated following reactor shutdown
- upon reactor shutdown system thermal power level still significant percentage of operating reactor power due to heat load generated by fission product radiation (decay heat)
- as short half-life radioisotopes disappear from nuclear fuel, decay heat power decreases

Slide 23 – decay heat production following reactor shutdown graphic

- graphic from 1975 Reactor Safety Study shows decay heat load following reactor shutdown as percent of operating reactor power prior to shutdown versus time in seconds
- note log scales for both time and percent power

- at one year following reactor shutdown, decay heat power is about 0.05% of reactor operating power

Slide 25 – example PWR RHR system graphic

- graphic illustrates one of redundant residual heat removal loops for typical PWR (similar for BWR)
- system connected to primary coolant system by opening valves and starting RHR pump
- heat from RHR heat exchanger transferred to component cooling water heat exchanger and then to ultimate heat sink via plant service water system

Slides 28 – fuel rod assembly

- first and second fission product retention barriers
- most fission products retained within fuel pellet ceramic matrix
- as long as fuel rod cladding remains intact all fission products, including more volatile types like halides and noble gases, retained within fuel rod

Slide 33 – NPP operational transient/accident safety objectives

- operational transient/accident safety objectives serve as bases for nuclear power plant's engineered safety features
- reactor core reactivity control, core heat removal, and fission product containment safety objectives, similar to defense-in-depth level 1 operational safety objectives
- reactor coolant inventory control and reactor containment building heat removal capability additional safety objectives for operational upset and accident events

Slide 34 – engineered safety features and functions

- engineered safety feature <u>functions</u> common to all light-water reactor systems, although individual ESF <u>system configurations</u> differ depending on reactor type and vendor
  - reactor protection systems differ for PWR and BWR due to reactor system design differences
  - emergency core cooling system configurations differ by reactor type (PWR vs BWR) and PWR vendor (Westinghouse, Babcock & Wilcox, Combustion Engineering)
  - post-accident heat removal systems differ because of differences in PWR and BWR containment system designs
- ESF systems redundant and independent safety systems

Slide 35 – reactor protection system graphic

- <u>redundant</u> reactor protection system ensures reactor core fission chain reaction terminated for all off-normal operating conditions and events by rapid insertion of control rods into reactor core
  - in PWR, where control rod drive mechanisms located on top of reactor vessel, rapid insertion achieved by gravity when control rods released from drive mechanisms

  - — in BWR, where control rod drive mechanisms located below reactor vessel, rapid insertion achieved using high pressure nitrogen to drive control rods into reactor core
- numerous signals from redundant plant safety-related monitoring instrumentation can cause reactor trip